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Land subsidence threats and its management in the North Coast of Java

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Abstract. Cities on the north coast of Java such as Jakarta, Semarang, Pekalongan, and Surabaya are vulnerable to environmental pressures such as sea level change and land subsidence. Land subsidence can be caused by natural and anthropogenic processes. Geologically, the north coastal plain of Java consists of unconsolidated Holocene alluvial deposit. The recent alluvial deposit is prone to compaction, and further aggravated by anthropogenic forces such as groundwater extraction and land development. Understanding the complex interaction of natural and manmade factors is essential to establish mitigation strategy. Although the impacts of land subsidence are widely felt, many do not realize that land subsidence is taking place. This paper presents a brief review of the land subsidence threats in the North coast of Java and proposes a recommendation for suitable management response.

1. Introduction

Cities located in the low lying coastal areas are vulnerable to environmental changes such as sea level change and land subsidence. Currently, the observed subsidence rates in coastal megacities are exceeding the sea level rate by a factor of ten [1]. More than half a billion people live in this kind of areas and are vulnerable to the risks of coastal flooding, wetland loss, shoreline retreat and loss of infrastructure [2]. Land subsidence is defined as the gradual vertical movement of the earth surface due to the subsurface movement of the earth materials. Land subsidence problem can arise from natural and anthropogenic problems or combination of both. Natural subsidence can result from processes such as tectonics, sediment compaction, peat oxidation and isostatic adjustment [3–6]. Man-induced causes are due to fluids, gas and solids extraction, and the addition of surface loads [7–9].

It is reported that there were over 150 areas of recent land subsidence across the world, particularly along the coasts, industrialized and densely populated areas [10]. Like other countries, Indonesia is also vulnerable to land subsidence hazard. Java is the most densely populated island of Indonesia, hosting about 60% of the total Indonesian population. During the last 50 years, industrialization and urbanization have transformed the rural, agricultural Java Island into a mixed rural-urban to a mega-urban area [11,12]. The large population and increasing anthropogenic activities have brought about more pressures towards the subsurface environment. The north coast of Java hosts main cities and urban areas including the capital Jakarta. The north coast Java road is a vital hub connecting the west part to the eastern part of the island. Natural and anthropogenic forces are thought to have contributed to land subsidence occurrence in this area.

Land subsidence is a subtle process, affecting a large area and going on at a slow rate. Many do not realize that it is taking place until the impacts are felt. Increasing coastal floods, sea water intrusion, failure of well casings, differential settlements, cracks and other damages of buildings and infrastructures are some of the impacts of land subsidence. Estimation of the economic costs of land

subsidence is enormous, for Semarang city alone could reach 3.5 trillion Rupiah [13]. This paper is aimed to present a brief review on land subsidence in the North Coast of Java Island. The paper discusses the main features of the land subsidence including the subsurface geology, land subsidence monitoring, analysis of possible causes and mechanism. At the end, this paper proposes a suitable management response to tackle this ongoing land subsidence problem.

2. Geology and engineering geology of the Northern Java alluvial plain

The northern Java alluvial plain extends from the west of Serang-Jakarta-Cirebon plain to Brebes-Pekalongan plain, Semarang- Rembang plain and ends at the east at Surabaya plain (Figure 1). Northern alluvial plain of Java consists of unconsolidated clay, silt, sands, and gravels of Quaternary age [14]. The hydrogeology of unconsolidated alluvial plain occurs as multi aquifers and aquitards system. Aquifers in the alluvial plain occur as lenses, interbedded with thick aquitards [15–17]. As the municipal water supply is limited, the population and industries mostly rely on groundwater [18]. Over exploitation of groundwater aquifers causes lowering of the piezometric head and induces dewatering of compressible aquitards. Aquitards are saturated, a highly compressible material with low hydraulic conductivity. Subsidence follows the dewatering of aquitard which does not occur immediately due to the low hydraulic conductivity of the layer.

Engineering boreholes along the North Java coast showed similar characteristics of aquitards particularly at the upper 20m depth [19,20]. Typical engineering properties related to the consolidation of North Java clay are presented in Table 1. Table 1 suggests that the clay is of soft consistency, low hydraulic conductivity and highly compressible.

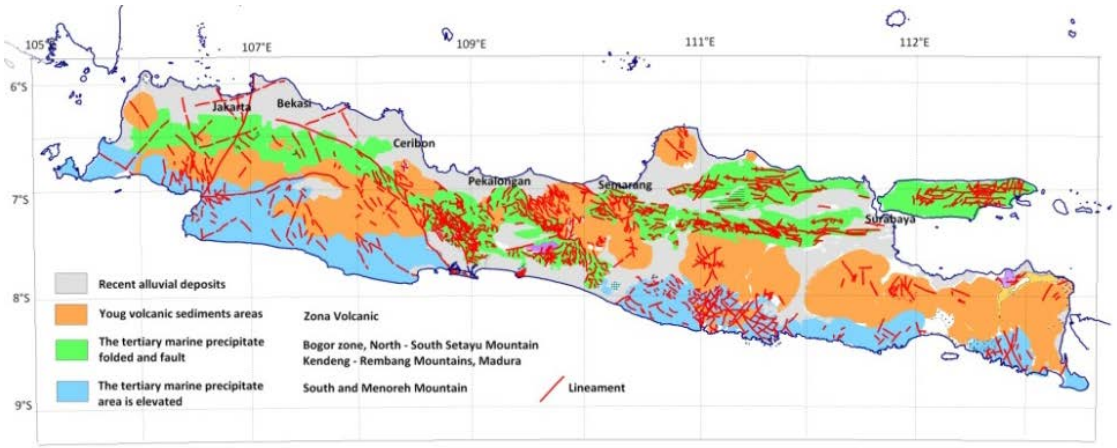

Figure 1. Physiography of Java [14]**.**

Table 1. Consolidation properties of typical North Java clay.

Location	Unit weight (kN/m^3)	Hydraulic conductivity k (m/s)	Coefficient ofconsolidation C_v (m^2/year)	Coefficient of compression (c_c)	Reference
Semarang clay	15.0-18.3	$1.0x10^{-10}$	0.2-1.1	0.2-0.6	[15,21]
Jakarta clay	15.0-17.6	$1.26x10^{-09}$	3.0-4.0	0.2- 0.5	[22]
Surabaya clay	14.9-19.0		1.8- 2.0		[23,24]

3. Land subsidence rates and mechanism

Monitoring of land subsidence in the cities of Jakarta, Pekalongan, Semarang, and Surabaya had been carried out by several researchers using different methods. The methods are leveling, GPS survey and interferometry using SAR images. Monitoring of land subsidence in the studied locations was not at

regular intervals and not always using the same method. Below are the highlights of monitoring and mechanism of land subsidence occurring in the North Java cities:

3.1. Jakarta

Several land subsidence measurement techniques was being employed in Jakarta over the period of 1982- 2010 [25–28]. In general, the subsidence rate varies spatially and temporally of about 1-10 cm/year and at some places could reach to 25-28 cm/year [29]. The high rate of subsidence is associated with the high rate of groundwater extraction. The groundwater extraction in Jakarta is high as reflected by the piezometric head decline of 0.2- 2 m/year [30]. However study by [31] revealed that hydraulic pressure, more than hydrostatic, occurred in Tongkol, North Jakarta where subsidence was also taking place. The existence of this overpressure indicated that apart from anthropogenic factors, natural compaction may also contribute to land subsidence process in Jakarta.

3.2. Semarang

Land subsidence in Semarang has been extensively studied from many aspects: geodetic monitoring, groundwater extraction, and engineering geology. Geodetic measurements during 1980 until 2010 revealed that the land subsidence rate varied spatially from 1-10 cm/year, getting higher towards the north coast [28,32,33]. Overexploitation of groundwater extraction is thought to contribute towards the fast subsidence rate. Microgravity studies [34,35] revealed that there is a deficit of groundwater due to overexploitation particularly in Kaligawe and Genuksari areas. It is corroborated by groundwater level measurements showing fast lowering of the piezometric head [36]. [15,37] used the subsurface properties to quantify the rate of land subsidence. Comparing the calculated rate of subsidence to the geodetic monitoring results, we found that the geodetic rate exceeds the calculated rate by 1.0- 2.0 cm/year. [21] observed from the occurrence of excess pore pressure from CPT test in the north east of Semarang, indicating the possibility of natural compaction. Provided the geodetic rate is consistent, the discrepancy of land subsidence rate may arise from unquantifiable natural driving factor.

3.3. Pekalongan and Surabaya

Limited information is available from published literature about the land subsidence of Pekalongan and Surabaya. However, monitoring studies revealed that land subsidence occurred in the area. Time series analysis of InSAR images revealed that subsidence occurred in Pekalongan at the rate of 4.8-10.8 cm/year, suspected to be caused by groundwater withdrawal for agriculture [28]. GPS monitoring during 2007-2010 in Surabaya showed subsidence rate of 1.0 - 2.7 cm/year occurring in industrial and built areas [38]; possibly related to groundwater withdrawal.

4. Analysis and proposed recommendation

Research on land subsidence in the North Java coast can be categorized into monitoring by geodetic methods, engineering geology characterization, and predictive numerical modeling. Intensive studies were mostly conducted in large cities such as Jakarta and Semarang where the impacts of land subsidence are mostly visible. Analysis of the hydrogeology and engineering geology of the North Java coastal plain suggests that the thick compressible deposit is prone to compaction due to natural and man-induced causes. Although many type of research have been conducted, subsidence has not been halted, and there are still some challenging issues regarding land subsidence in the North Java coastal area. Some of the matters are:

4.1. Subsurface characterization

The vast area of North Java requires detailed subsurface lithologic and engineering characterization. Information of the subsurface condition is not restrictive to land subsidence issue but greatly benefit regional development purposes.

4.2. Monitoring of groundwater level and land subsidence rate

Previous monitoring of groundwater level and subsidence rate had been intermittent, and many have been discontinued.

4.3. Information gap between scientific publications and stakeholders

Although the damages due to land subsidence are widely visible, no specific actions have been imposed to mitigate the impacts. The lack of awareness of the public and stakeholders could be attributed to the insufficient knowledge regarding the land subsidence process and mechanism and also the magnitude of the economic impacts due to subsidence.

Based on the above analysis, some recommendations are proposed:

- Continuous, long-term groundwater monitoring and land subsidence monitoring
  Groundwater monitoring data is useful to assess the groundwater balance condition and to determine groundwater control measures. Monitoring of subsidence could be achieved by regular GPS campaign, interferometry using satellite images, borehole extensometer or simply installation of stable benchmarks.
- Subsurface engineering and hydrogeological investigation
- Bridging scientific information into administrative policy and control
  Results of scientific research should be the basis of administrative policy and control. For example the subsurface condition, results of groundwater level and subsidence monitoring could be used as the basis of groundwater withdrawal regulation and control measures. Scientific information also should be the basis of land subsidence disaster management measures, for example charging up the aquifers through artificial recharge, building flood retaining dikes, pump stations, etc.
- Active involvement of local stakeholders
  Successful mitigation of land subsidence requires the active participation of local stakeholders, particularly for monitoring, formulation of local regulation and control measures.

5. Conclusions

Industrialization and urbanization have been rapidly experienced in the North Java coastal area. For the last three decades, this area has changed considerably and such trend is expected to continue shortly. Consequently, the demands for land usage and groundwater resource will be accelerated to cater the increasing population and development. Land subsidence is likely to continue in the cities of Jakarta, Semarang, Surabaya, and Pekalongan and may occur in other cities along the North Java coast as well. Therefore, prevention of land subsidence and mitigation of land subsidence induced hazards will continue to be a demanding task for governments, engineering geologists, and geotechnical engineers. Recommendations are proposed in attempts to halt land subsidence rate and minimize its impacts.

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